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Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review

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ABSTRACT

The call for reduction in pollution has been mandated by government's policies worldwide. This challenges the engine manufacturer to strike an optimum between engine performance and emissions. However with growing technology in the field of fuel injection equipment, the task has become realizable. For past few years it has been the hot topic to improve combustion and emissions of compression ignition engines through optimizing the fuel injection strategies. Choosing between various injection strategies are potentially effective techniques to reduce emission from engines as injection characteristics have great influences on the process of combustion. For example, increasing the fuel injection pressure can improve the fuel atomization and subsequently improve the combustion process, resulting in a higher brake thermal efficiency, producing less HC, CO, PM emissions, but more NO_x emission. Pilot injection help in reducing combustion noise and NO_x emissions and immediate post injection may help in soot oxidation and late post injection helps in regeneration of diesel particulate filter. This article aims at a comprehensive review of various fuel injection strategies *viz* varying injection pressure, injection rate shapes, injection timing and split/multiple injections for engine performance improvement and emissions control. Although every strategy has its own merits and demerits, they are explained in detail, in view of helping researchers to choose the better strategy or combination for their applications.

Contents

1. Introduction

Diesel engines are the most efficient energy conversion devices; however they have one serious drawback: the amount of exhaust emissions like NO_x and particulate matter (PM) is comparatively larger than that of gasoline engines. According to

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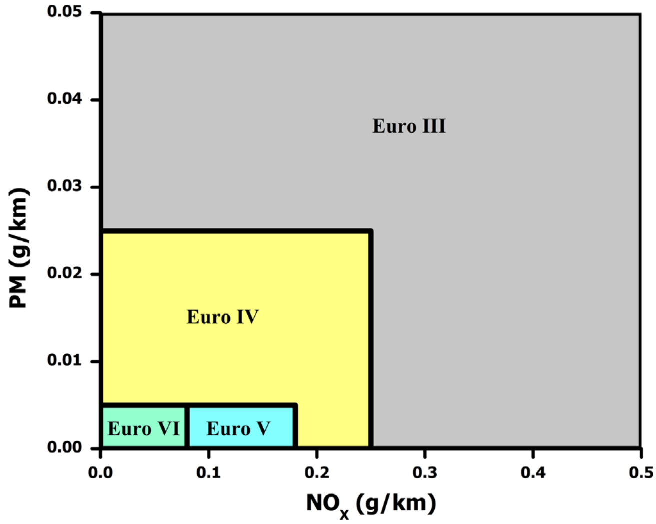

Fig. 1. European emission standards for passenger diesel cars.

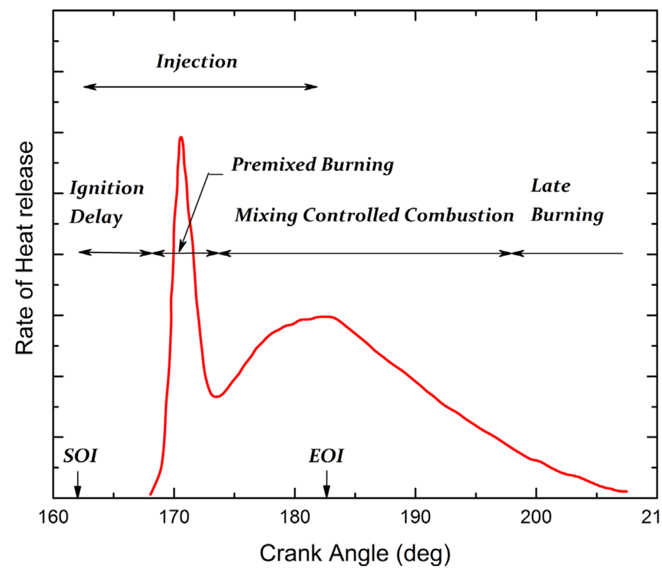

Fig. 2. Typical heat release rate curve of a CI engine (redrawn from [9]).

various reports [1–7], the exhaust emissions from engines have undesirable effects on human health. The reduction of environmental pollutions from diesel engines is regulated by federal government regulations. In order to improve the air quality standards, regulations on emissions from mobile sources have become stringent drastically in USA, Japan, Europe and other Asian countries over the decade. The European emission standards implement progressive and increasing stringent emission norms on passenger diesel cars [8] shown in Fig. 1. These regulations have pressed the automobile industries to explore substitutes to conventional fuel injection systems and have enthused attention in development of various fuel injection strategies.

The emissions formed are dependent upon the engine design, power output and working load. The complete combustion of fuel leads to major reductions in the formation of exhaust emissions. Complete combustion is a result of careful matching of air–fuel mixture and accuracy in the injection process. In order to reduce NO_x and PM formation it is necessary to understand the mechanisms of its formation.

1.1. NO_x and PM formation

Generally, the combustion process in a typical CI engine can be classified into four major phases [9], as shown in Fig. 2, the heat release rate curve of a CI engine.

The four phases are ignition delay, premixed burning, mixing controlled combustion and late burning phase. The period from the start of fuel injection to the start of combustion is the ignition delay. During the premixed combustion phase, a rapid heat release from the combustion of fuel which premixes and accumulates during the ignition delay period takes place. A relatively slower and controlled mixing combustion takes place after the initial rapid premix burning, which is primarily governed by the fuel atomisation, mixing of fuel vapour with air and chemical reactions. In the late combustion phase, the heat release rate slows down to a lower rate extending itself into the expansion stroke.

During the premixed combustion phase, poly aromatic hydrocarbons are formed which are the precursors of soot, due to the lack of air and fuel rich environment. The controlled mixing combustion phase takes place in two spatially separated stages. In the first stage, the fuel passes through a high fuel-rich premixed reaction zone and then in the second stage the fuel burns out in the turbulent diffusion flame at the jet periphery. Thus, for both combustion phases—initial premixed and controlled mixing; the fuel mixes with air, and gets vaporized and heated to ignition temperature. Then the fuel gets partially oxidized in a rich premixed reaction, and then completes combustion in a near-stoichiometric diffusion flame. The fuel rich premixed combustion produces partially burned products which lead to formation of soot. Though most of the soot burns out with the remaining fuel at the late combustion phase, a small part is not oxidized and converts to exhaust emission. Oxides of nitrogen (NO_x) are formed in the high-temperature regions in the hot product gases, and the rate of production increases exponentially with temperature. The NO_x and particulates are traded off against each other in several characteristics of engine design. High temperatures inside the combustion chamber help in reduction of particulates at the expense of high NO_x formation. At the same time low temperature inside the combustion chamber leads to less NO_x formation but increases the likelihood of high particulates formation. Thus a trade-off between NO_x and PM formation is more important to minimize both emissions [10].

1.2. Injection strategies

There are several ways to reduce NO_x and PM emissions. In some cases exhaust gas recirculation (EGR) is used to reduce NO_x emissions [11–14], but it increases the PM emissions and also increases the soot deposits on engine components and decreases the durability of the engines. In EGR, the exhaust gas displaces the fresh air entering the combustion chamber; as a consequence lower amount of oxygen in the intake mixture is available for combustion. Reduced oxygen available for combustion lowers the effective air–fuel ratio. The specific heat of intake mixture also increases by addition of exhaust gas, which results in reduction of flame temperature. Thus combination of lower oxygen content and reduced flame temperature reduces the rate of NO_x formation while increases the PM emissions accompanied by power loss [15]. The other ways to reduce emissions are by implementing various exhaust gas after treatment devices such as diesel particulate filter (DPF) and selective catalytic reduction (SCR). DPF is able to capture and remove diesel particulate matters and soot, while SCR can convert NO_x emissions to nitrogen and water by catalytic reactions. Though after treatment devices promises to reduce NO_x and PM emissions to a greater extent [16–23], but results in high capital and maintenance cost. Though there are many emission reduction techniques available, reducing the pollutants at source is the most beneficial method. The modern electronic fuel injection

system is known to keep the emission levels within limits without compromising the performance of the engine and will continue to play a vital role in the development of improved diesel engines for the foreseeable future. The following principles and strategies improves fuel–air mixing and diffusion combustion process that leads to reduction of both NO_x and particulates formation [24,25]

- Injection pressure level controls spray penetration and improve atomization.
- Fuel should be distributed mainly within the air inside the combustion chamber with minimum possible wall wetting.
- Nozzle configuration, such as, number of spray holes, diameter, orientation, nozzle tip protrusion inside the combustion chamber, all affect fuel distribution and atomization within the combustion chamber.
- Use of variable injection timing and variable injection rate technology.

In the past, mechanical fuel injection systems with an average injection pressure of 200–300 bar were used, and only one injection per cycle was allowed. Due to poor mixing with air, the resulting cloud of fuel had wide range of temperature in the combustion chamber. The combustion in the fuel rich region of the flame produced soot, and the leaner regions produced NO_x. To overcome this, electronic fuel injection systems today operate at high pressure and have more number of holes per injector. For multiple injection holes, the fuel clouds are smaller than those from a single injector hole. The temperature difference across the spray clouds is far narrower; this offers better air utilization within the combustion chamber and leads to reduction in emissions. The electronic fuel injection systems are replacing the conventional mechanical systems in the high speed DI diesel engines. The benefits of electronic fuel injection systems [26] are

- Very high fuel injection pressures up to 2500 bar to atomize fuel into very fine droplets for fast vaporization.
- High velocity of fuel spray that penetrates the combustion chamber within a short time to fully utilize the air charge.
- Precisely controlled injection.
- High accuracy of fuel metering to control power output and limit smoke.
- Variations in the quantity of fuel injected among different cylinders are drastically minimized.
- Controlled initial rate of injection to reduce noise and emissions.
- Sharp end of injection to eliminate nozzle dribble, prevent nozzle fouling and reduce smoke and hydrocarbon emissions.
- Injection rate shaping for controlling heat release rates during premixed and diffusion combustion phases for reducing noise and formation of smoke and NO_x.
- Split injection to avoid rapid heat release rate at the start of combustion and prevent NO_x formation.

Most of these injection strategies employed, directly or indirectly influence the fuel spray formation inside the combustion chamber. Thus the fuel spray plays a vital role in the combustion phenomena inside the compression ignition engines. Though many researchers adopt various injection strategies as a tool to reduce emissions and improve engine performance, but there is no comprehensive review on this topic found in literature. From this point of view, the purpose of this paper is to review the various fuel injection strategies *viz* injection pressure, injection timing, injection rate shaping and split/multiple injections in CI engines to simultaneously improve performance and reduce the exhaust emissions.

2. Injection pressure

The search for better combustion in the field of diesel engines, regardless the engine size and application, has a strong link to the capability of the fuel injection equipment to generate high injection pressure. Spray properties are improved by higher injection pressure. Usually the spray penetration length increases with higher injection pressure and low ambient density, while the spray angle increases with increase in ambient density. Fuel injection pressures range from 200 to 2500 bar based on the fuel injection systems used. Research has shown that by further increasing the injection pressure more benefits in terms performance and reduction in emissions are to be realized [27,28].

Spray penetration is improved at higher injection pressure [29–32]. The speed and extent to which fuel penetration occurs inside the combustion chamber decides the air utilization and the fuel–air mixing rate. In some combustion chamber design, where high swirl ratio and hot walls are achieved requires greater penetration for proper combustion of fuel however in case of multi hole injection, the probability of spray hitting the cold regions may produce more unburned or partially burned emissions. For lesser spray penetration may lead to improper mixing rate and poor air utilization which leads to high emissions. Thus the spray penetration is an important factor in deciding the engine emissions, which requires careful optimisation of injection pressure for varying speed and load conditions. Thus the spray penetration length prediction becomes more important and interesting for more researchers. Dent [33] predicted the spray penetration length L_{tip}, based on a gas jet mixing model for the spray as shown in Eq. (1)

$$L_{tip} = 3.07\left(\frac{\Delta P}{\rho_g}\right)^{1/4}(tD_n)^{1/2}\left(\frac{294}{T_g}\right)^{1/4} \tag{1}$$

where ΔP is the pressure drop across the nozzle, t is the time after the start of injection, and D_n is the diameter of the nozzle hole, ρ_g is the ambient density, T_g is the ambient temperature. This model predicts the spray penetration length at best for nozzles where $2 \le (L_n/D_n) \le 4$ and for $t > 0.5$ ms but at high ambient densities i.e. $p > 100$ atm, the model over predicts the penetration. Hiroyasu et al. [34] based on diesel injection in high pressure chambers, predicted the penetration length as a function of time, ambient conditions and injection pressure. According to their model the penetration length increased as a function of time t until jet broke up, immediately after the break up, the penetration increases as function of $\sqrt{t}$. The Hiroyasu model is given by Eqs. (2) and (3)

$$t < t_{break} : L_{tip} = 0.39\left(\frac{2\Delta P}{\rho_l}\right)^{1/2} t \tag{2}$$

$$t > t_{break} : L_{tip} = 2.95\left(\frac{\Delta P}{\rho_g}\right)^{1/4}(tD_n)^{1/2} \tag{3}$$

where

$$t_{break} = \frac{29\rho_l D_n}{(\rho_g \Delta P)^{1/2}},$$

ΔP is the pressure drop across the nozzle, t is the time after the start of injection, and D_n is the diameter of the nozzle hole, ρ_l, ρ_g are the liquid fuel and ambient density.

2.1. Effect of injection pressure on different fuel

The injection pressure has a significant effect on performance and emissions formations. In general, increasing the injection pressure causes an earlier start of combustion because of improved atomisation which results in better air fuel mixing. As

a result of this, the cylinder charge gets compressed as the piston moves towards top dead centre (TDC) resulting in relatively higher temperatures during combustion which facilitates increased NO_x formation due to high premixed heat release rate and lowers the HC formation. Similarly due to lower ignition delay period at high injection pressure, engine power output gets improved, resulting in better BSFC and on contrary lower injection pressure results in poor BSFC due to longer ignition delay because of deteriorated atomisation and mixing process. Many literature are found in support of the above theory. Icıngur and Altiparmak [35] studied the effects of fuel injection pressure on diesel engine performance and emissions. They studied the effect of lower injection pressures of 100, 150, 200, 250 bar. They found that at higher pressure of 250 bar, NO_x was increased and smoke was decreased. They also found some considerable increase in torque and power output from the engine. Celıkten [36] investigated the effect of injection pressure on engine performance and exhaust emissions in indirect injection (IDI) engine. He also varied the injection pressure from 100 to 250 bar in steps of 50 bar. Interestingly, he found that 150 bar injection pressure resulted in maximum performance, after which the performance deteriorated. This may due to the fact that for IDI engine, a too high fuel injection pressure may lead to more fuel burnt in the swirl chamber/prechamber, resulting in a slightly reduced output power. They also found that higher injection pressure reduced SO_2, CO_2 and O_2 while lower injection pressure was preferred for decreased NO_x and smoke emissions.

Recently, bio-diesel fuels promise clean, alternative and renewable source of energy. Bio-diesels have a number of properties that make it an excellent alternative fuel for diesel engines [37–41]. Fuel injection pressure also plays a key role in improving the performance and emission characteristics of other alternate fuels like biodiesel and its blends with diesel. Gumus et al. [42] reported the effect of fuel injection pressure on diesel engine fuelled with biodiesel-diesel fuel blends. They examined the effect of four different injection pressures 180, 200, 220, 240 bar on performance and exhaust emissions. The BSFC of higher percentage biodiesel-diesel blends decreased with increased injection pressure, smoke, HC and CO also increased but CO_2, O_2 and NO_x decreased. Sayin and Gumus [43] investigated the impact of injection pressure on performance and emission of biodiesel-diesel blends. The increased injection pressure gave better results for BSFC, BTE and BSEC compared to original and reduced injection pressures because of finer breakup of fuel droplets which provided increased surface area and better mixing with air leading to better combustion. Smoke, HC and CO decreased while NO_x emissions were increased with increase in injection pressure for all fuel blends. Canakci et al. [44] examined the effect of injection pressure on the performance and emission characteristics of diesel engine fuelled with methanol blended diesel fuel. They used three different injection pressures 180, 200, 220 bar to study its effect on four different loads 5, 10, 15 and 20 Nm at constant engine speed of 2200 rpm. The results showed that with increase in injection pressure NO_x and CO_2 increased while smoke, CO and HC decreased. On contrary performance parameters like BSFC, BSEC and BTE were best at original injection pressure of 200 bar and gets poor on either increased or decreased injection pressure. It was also notable that peak in-cylinder pressure and heat release rates increased with increased injection pressure. This may due to the fact that the fuel injection timing is designed and fixed for the injection pressure of 200 bar, a higher fuel injection pressure may lead to an earlier combustion before TDC, resulting in a higher peak in-cylinder pressure. In another words, the fuel injection timing can be retarded to meet the increased fuel injection pressure, thereby further improving the performance. Purushothaman and Nagarajan [45,46] examined the effect of injection pressure on heat release rate and emissions on diesel engine fuelled with orange skin powder diesel solution. They used three different injection pressures 215, 235 and 255 bar. For injection pressure of 235 bar, they obtained increased peak cylinder pressure, BTE and peak heat release rate, NO_x also increased by 26%, whereas CO, HC and smoke decreased by 39, 66 and 27% respectively for 30% orange skin powder solution compared with diesel fuel. Puhan et al. [47] investigated the effect injection pressure on high linolenic linseed oil methyl ester fuelled diesel engine. At higher injection pressure of 240 bar, thermal efficiency and BSFC is improved accompanied with decreased CO, smoke and HC but slight increased NO_x emissions. The effect of injection pressure on *Jatropha* methyl ester fuelled engine was investigated by Jindal et al. [48]. They chose three injection pressures 150, 200, 250 bar for their study. It was found that at injection pressure of 250 bar, BTE was improved by 8.9%, with a reduced HC and smoke compared to the base injection pressure. Pandian et al. [49] studied the effect of injection pressure on *Pongamia* biodiesel blends. The injection pressure was varied from 150 to 250 bar in steps of 25 bar. The significant finding was when injection pressure was increased from 150 to 225 bar, the BTE got improved with lesser BSEC and also CO, HC and smoke emissions were reduced but NO_x emissions were increased. However when further increased the fuel injection pressure, the results were negated due to fixed fuel injection timing. Belagur and Chitimini [50] evaluated the effect of injection pressure on the performance, emission and combustion characteristics of diesel engine fuelled with hone oil and its blends. They also reported that by increasing the injection pressure, BTE and NO_x emissions were increased but CO, HC and smoke emissions were reduced. It was also found that upon increasing injection pressure, the ignition delay got reduced. A recent study by Kannan and Anand [51] on the effect of injection pressure on engine performance and emission with biodiesel derived from waste cooking oil revealed that by increasing injection pressure at 25.5° bTDC had significant improvement on BTE, in-cylinder pressure and heat release rate with reduction in NO_x and smoke emissions. From the above review, it can be found that with the increase of fuel injection pressure, for both diesel, biodiesel or blend fuel, the performance is improved, the fuel consumption is reduced, the major emissions such as HC, CO and PM are reduced but with a slight increase in NO_x emissions. Furthermore, for a significantly increased fuel injection, the fuel injection timing should be retarded to meet the new operating conditions; otherwise, the performance could be deteriorated due to earlier combustion.

2.2. Effect of ultra-high injection pressure

Since the introduction of electronic fuel injection equipment, higher injection pressure has become practical solution to improve performance and reduce emissions. In early times, 1000 bar injection pressure with an inline or a rotary pump system was considered to be high pressure. But in recent times, the pressure has been raised to 1600–1800 bar and even beyond 2000 bar. The high pressure makes the spray droplets near the nozzle susceptible to breakup processes, however with rapid declines in droplet diameters, droplets further away from nozzle becomes less susceptible to aerodynamic breakup even though they still possess velocities of up to 200 m/s [52]. Pierpont and Reitz [53] studied the effect of high injection pressures on the engine performance and emissions. When injection pressure was increased from 720 to 960 bar, there was a decrease in PM. When injection pressure was increased from 960 to 1220 bar, there was a substantial improvement, however when further increased to 1600 bar, there was only a small gain because the driving torque required by the fuel pressure to decrease particulate could not compensate the deterioration in BSFC. Also higher injection pressure led to higher

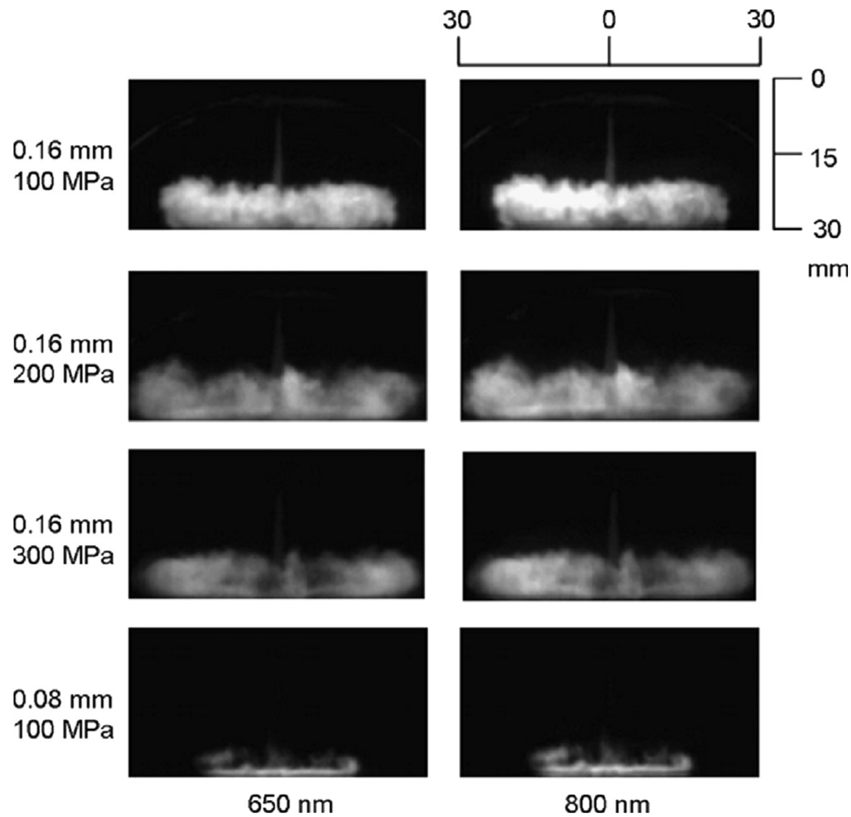

Fig. 3. Effect of ultra-high injection pressure on soot luminosity and flame size at end of injection [57].

premixed combustion which contributed to an increase in NO_x. It was also noted that when injection pressure was increased from 720 to 1600 bar, there was an increase of 3% in BSFC to maintain NO_x level constant. So this study concluded that on higher injection pressure, increase in NO_x emission was substantially high which overruled the reduction in particulates and BSFC. Su et al. [54] examined increased injection pressure up to 1600 bar in diesel engine as well as some spray tests were also carried out. The results showed that increased injection pressure led to lower PM and higher NO_x. The lower PM was attributed to smaller average drop sizes, as measured by the sauter mean diameter (SMD). Dodge et al. [55] reported that the use of high injection pressure significantly reduced soot formation and PM emissions with slight increase in NO_x emissions. However, a significant penalty of using very high injection pressure was increased BSFC which was expected due to higher friction on the injector cam and to irreversible energy losses in compressing the fuel in the plunger barrel. Also another potential penalty in using high injection pressures was increased injection cam wear in the fuel injection pump. Pickett and Siebers [56] studied the effect of injection pressure on soot in diesel fuel jets injected into high temperature high pressure constant volume combustion vessel. An increase in injection pressure caused a decrease in soot levels due to coupled effects of decrease in the amount of air entrainment and fuel air premixing that occurred upstream of the lift off length and a decrease in the residence time in the fuel jet sooting regions due to higher injection velocities. The peak soot in the fuel jet decreased linearly with the increasing injection velocity. Wang et al. [57] studied the effect of ultra-high injection pressure on flame structure and soot formation in constant volume combustion vessel. Fig. 3 shows the effect of injection pressure on soot luminosity and flame size. It was reported that soot luminosities and flame size at injection pressure of 1000 bar were appreciably stronger and smaller respectively than those of 2000 and 3000 bar. However, when integrated soot luminosity was calculated by summing up the grey scale intensities of all the pixels, interestingly, reduction in soot luminosities was achieved when injection pressure increased from 1000 to 2000 bar, however, when further increased to 3000 bar there was no significant change (Fig. 4). The soot reduction with increase in injection pressure was mainly attributed to the better spray atomization and improved air entrainment.

The regulation of diesel engine exhaust particle emission is focussed on soot particles. The diesel soot particles are mainly composed of highly agglomerated solid carbonaceous material, ash, volatile organic and sulphur compounds. Fig. 5 [58] shows the typical particle size distribution of diesel soot. The nucleation mode is generally smaller in modal diameter than the soot mode. The formation of nucleation particles is considered to take place in the cooling dilution, outside the tailpipe, but in some cases they contain non-volatile fractions called core. The other mode is accumulation mode which is mainly related with carbonaceous agglomerates and the volatile matter adsorbed on their surface. The third mode consists of particles deposited on the engine cylinder and exhaust system walls and later reentrained [59].

Pagan [60] studied the effect of fuel injection pressure on particle size distributions emitted by diesel engines. The number size distribution shifted towards more nuclei mode particles as the injection pressure was increased. The general conclusion obtained from their study was that a decrease in the total number concentration at higher injection pressure and in some cases an increase in the number of nuclei mode particles were observed. Desantes et al. [58] investigated the influence of injection pressure on the aerosol exhaust particle size distribution. The accumulation mode particle number was generally found to be decreased and a sharp increase in the nucleation mode particle number was observed when the injection pressure was increased for some engine conditions. Lahde et al. [61] investigated the fuel injection

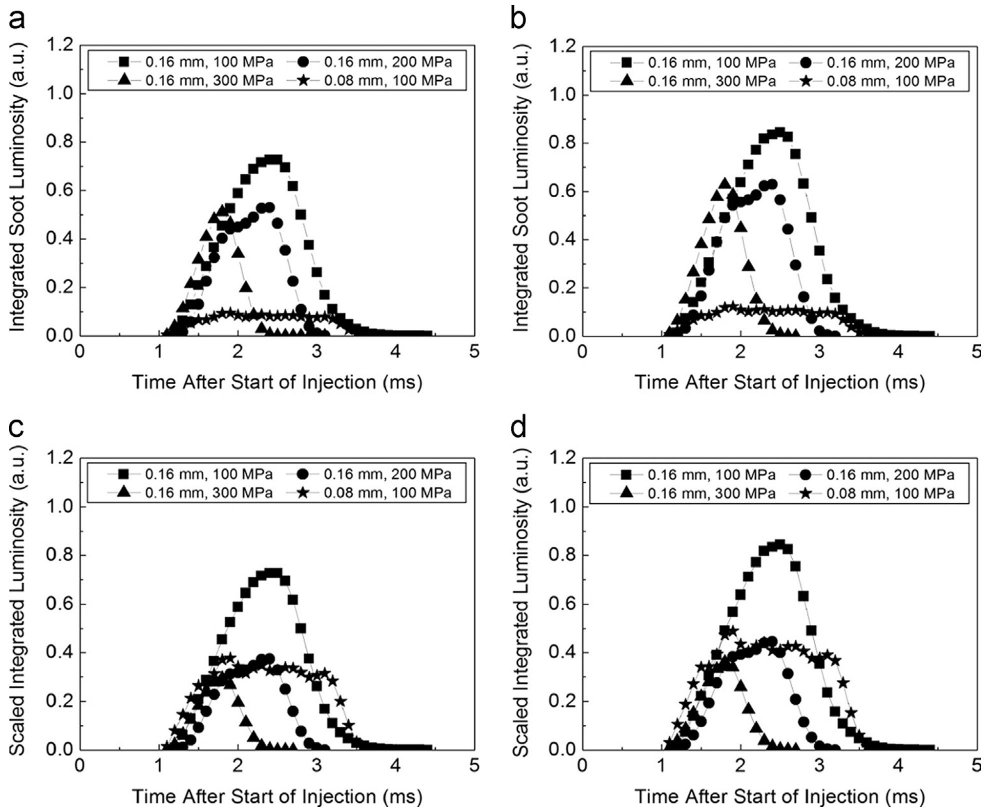

Fig. 4. Effect of ultra-high injection pressure on temporal integrated soot luminosity [57].

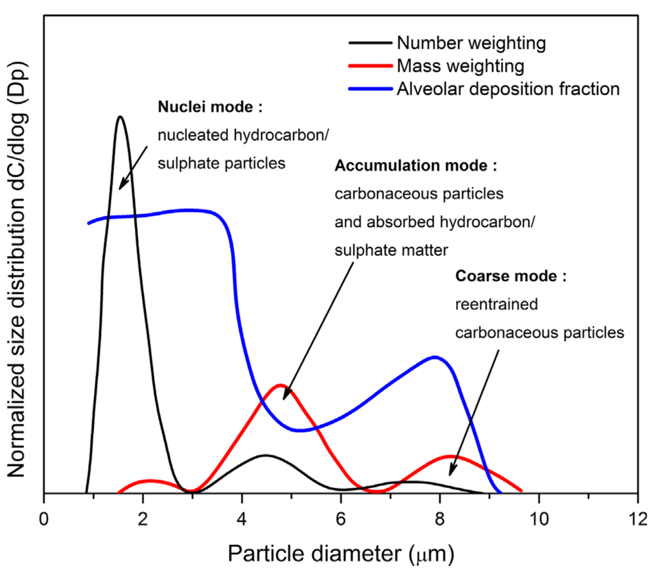

Fig. 5. Typical diesel soot particle size distribution (redrawn from [58]).

pressure on non-volatile particle emission. Their study revealed that increase in fuel injection pressure changed the dry particle size in all loads and number emissions of the core particles was dependent on injection pressure, i.e. the number of the core particles increased with increase in injection pressure however at low load, the mode was unstable or not detected. The size of core particles was around 5 nm at high loads for all injection pressure whereas it was below 5 nm and dependent on injection pressure at medium loads. Agarwal et al. [62] studied the effect of fuel injection pressure on diesel particulate size and number distribution. They reported that increasing fuel injection pressures, advancing the injection timing reduces the particulate number concentration due to advanced injection timing provide more time for mixing of fuel droplets before start of combustion. On the other hand lower injection pressures, number concentration first increases then decreases with retarding the injection timing due to improper fuel air mixing at lower pressures and less time before start of combustion. They also reported that the particulate surface area and volume distribution increases with increasing engine load and decreases with increasing injection pressure.

From literature, it is clear that significant reduction of soot emissions have been obtained by increasing injection pressures, with injection pressures ranging from 1000 to 2000 bar and above in some cases. However increasing injection pressure generally leads to increased NO_x emissions, but this can be offset by using rate shaping and more retarded injection timing with the help of same advancement in fuel injection equipment.

3. Injection rate shaping

Fuel injection rate shaping is a phenomenon to vary the injection rate over the course of a single fuel injection. As NO_x is produced at high temperature zones, which are highly dependent on the initial heat release rate, less quantity of fuel should be injected at the beginning of the injection phase, in order to limit initial heat release and NO_x formation. According to Herzog [63], that within the ignition delay period, the injection rate has to be small, with increasing load, the injection rate or the main injection should be increased. To control the injection rate, the parameters like injection pressure, spray hole diameter, number of spray holes and injection duration must be optimized.

In mechanical fuel injection systems, this was achieved by changing the cam profile [64], but it suffered a big disadvantage that it cannot be modified for different speeds and loading

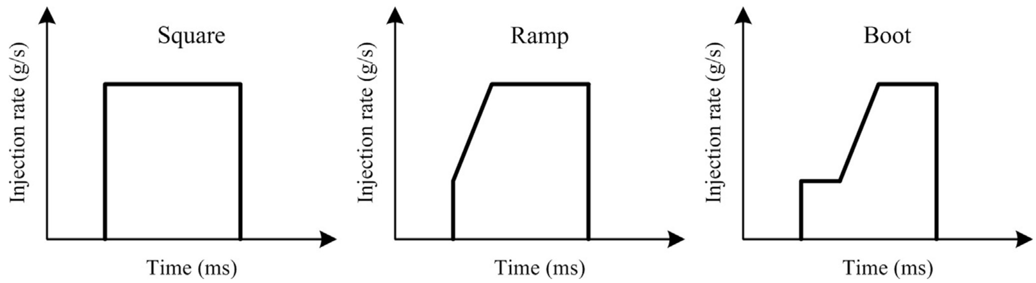

Fig. 6. Ideal square, ramp and boot type injections (adopted from [83]).

conditions of the engine. With advance in fuel injection technology and improvement in common rail electronic fuel injection systems, the fuel injection rate shaping has become true when Jose of Chrysler corporation filed their first patent on method of fuel injection rate control in 1993 [65]. In 1998, Ganser [66] published his results on design and testing of injection rate control (IRC) in a common rail injector. Some of the vital findings of his research include: the IRC works in the operating pressure range of 500–1500 bar, the amount of fuel injected with IRC during ignition delay period can be reduced maximum by a factor 4 and IRC is also possible with pilot injections which can be followed by main injection without IRC and the separation time between them is selectable. Though it was a pioneering effort in the injection rate control, but it fails to account for the change in engine performances with and without IRC. In the same year, Nishimura et al. [67] studied the effects of fuel injection rate on combustion and emission in a DI diesel engine. They studied the effect of pilot injection, gradual shaped injection profile using needle lift control and boot shaped injection profile using pressure control. They evaluated the effect of different fuel injection rates in terms of combustion, emission and combustion noise. They found that pilot injection helped in simultaneous reduction in NO_x and noise with minimum deterioration in smoke, with slow needle lift, they found both NO_x and smoke reduced but no substantial improvement in noise, with boot shaped injection control, it was found that smoke and combustion noise were greatly reduced with compensation of deterioration in fuel economy. These results were very promising to use injection rate control as an important factor in reducing emissions. As in electronic fuel injection system, the design of fuel injectors governs the fuel injection rate, which made many fuel injection equipment manufacturers to come up with an improved design of fuel injector nozzle assembly for effective rate shaping [68–79]. As injection rate shape also depends on the injection pressure, which is maintained constant using a common rail, results in nearly rectangular rate shapes. In order to overcome this difficulty, researchers [80,81] came up with a solution of using two common rails one with low pressure and the other with high pressure. With this type of next generation common rail system, they have achieved boot shaped fuel injection rate and when tested with single cylinder research engine, the results were very promising in improvement of NO_x – fuel consumption and NO_x – PM trade-offs.

Hwang et al. [82] studied the effect of fuel injection rate on pollutant for different engine speeds, loading conditions and swirl ratios. They optimized injection rate patterns for various engine conditions based on exhaust emissions. However, they did not address the effect of rate shaping on engine performance such as fuel consumption and thermal efficiency. The comparison between square, ramp and boot injection rate profiles were done by Benajes et al. [83]. Fig. 6 shows the ideal square, ramp and boot type injection rates. The comparison revealed that square pattern led to higher spray tip penetration due to the higher pressure at the start of injection, even if the injection duration was adjusted to match the same fuel quantity to be injected, while ramp always had medium penetration and boot had the lowest penetration. Interestingly the spray cone angles showed no change with different injection patterns. Beck and Chen [84] did a high speed combustion analysis on injection rate shaping and concluded that fuel quantity should be less than 10% of total fuel injected during pre-injection. In general with injection rate shaping NO_x was reduced with slight increase in the smoke and BSFC. Dober et al. [85] has studied the effect of injection rate shaping on combustion noise and concluded that slowest injection rate reduces combustion noise by 4.2 dBA at equivalent NO_x with little or no change in smoke performance. Desantes et al. [86] studied the effects of fuel rate shaping on engine performance and emissions. The boot type injection profile was generated using modified pump line nozzle systems. They varied different characteristic parameters of the boot type of injection like boot pressure, length and durations (see Fig. 7). Their interesting findings were: in general boot type injections, NO_x emission was reduced in expense of increased soot and fuel consumption, but it did not work at medium engine loads, since the increase in soot was higher than the relative decrease in NO_x emissions. However some specific boot shapes proved better emissions and performance trade-offs.

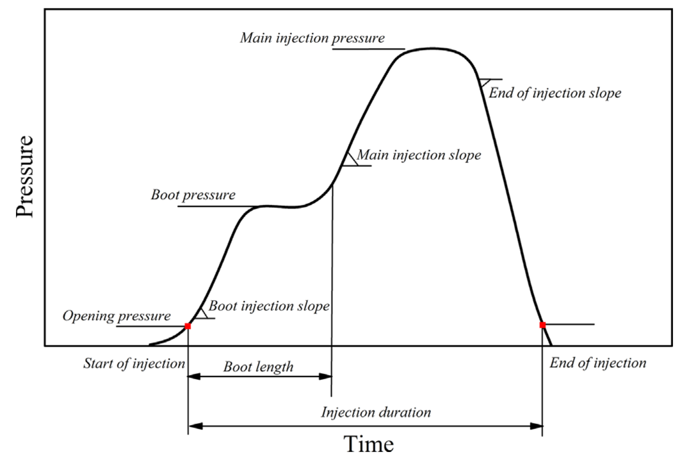

Fig. 7. Characteristics of fuel injection rate shape (redrawn from [86]).

Desantes et al. [87] also studied the effect of fuel rate shaping on engine combustion phenomenon. They found that, in general, any changes to the boot type injections produced evident changes in the diffusion combustion phase and boot type injections were more useful in reducing NO_x at high speed, high load conditions than in medium speed, low load conditions. Ghaffarpour et al. [88,89] also reported very similar results through numerical analysis using KIVA II CFD package. Their results also showed that injection rate shaping was effective in reducing NO_x emissions at high speeds and medium loads but ineffective for medium speeds and low loads.

Literature shows that injection rate shaping is a very effective strategy for reducing NO_x emissions at certain loading conditions. However, the reduction of NO_x accompanies an increase in fuel consumption and soot formation in most cases.

4. Injection timing

Injection timing plays a vital role in combustion process and pollutant formation. The injection timing affects the ignition delay because the air temperature and pressure change significantly close to TDC. As advancing the injection timing, the initial air temperature and pressure are lower so ignition delay will increase while retarding the injection timing i.e. closer to TDC when air temperature and pressure are slightly higher, results in shorter ignition delay. However, retarding or advancing injection timing beyond certain limits which varies from engine to engine may result in poor combustion. Injection timing variations also have strong effect on NO_x formation. Retarding injection timing, may help to control NO_x emissions with substantial penalty in fuel consumption, and also increasing unburned hydrocarbons, smoke and particulate emissions [9]. Therefore, finding an optimum injection timing for best performance and lesser emissions are required.

4.1. Effect of injection timing on different fuels

In general, biodiesel gives more NO_x emissions when used in diesel engine with same engine conditions due to various factors. One of the factors for higher NO_x emissions from biodiesel is because of its distinct properties like higher viscosity, isentropic bulk modulus and lower compressibility factor [90–94]. By varying injection timing from its default has proved to improve performance and emissions. Suryawanshi and Deshpande [95] studied the effects of fuel injection timing on *Pongamia* methyl ester fuelled diesel engine. With retarded injection timing, it was possible to achieve reduced NO_x, HC and CO emissions with negligible effect on fuel consumption rate. Similar trends were observed with BTE and exhaust gas temperature with retarded injection timing; however in-cylinder gas pressure and ignition delay was reduced. Nwafor et al. [96] reported that longer ignition delays by using rapeseed oil in diesel engine could be compensated by advanced injection timing with a penalty of increase in fuel consumption. Reddy and Ramesh [97] studied the effect of injection timing on *Jatropha* oil and concluded that by advancing the injection timing by 3° from original injection timing of diesel, increased BTE and reduced HC and smoke were observed. Ganapathy et al. [98] studied the influence of injection timing on *Jatropha* methyl ester. It has been observed that an advance in injection timing from default value caused considerable reduction in BSFC, CO, HC and smoke levels and an increase in BTE, maximum in-cylinder pressure, maximum heat release rate and NO_x emission. However retarded injection timing caused effects in the other way, hence an optimum injection timing was found for optimum balance between the performance and emission of *Jatropha* methyl ester compared to diesel. Sayin and Gumus [43] studied the impact of injection timing on biodiesel-blended diesel fuel. Three different injection timing were selected for the study, 15°, 20° and 25° bTDC. The original injection timing of 20° bTDC gave best results of BSFC, BSEC and BTE compared to advancing or retarding injection timing. Since advance injection timing gives more time for carbon oxidation, led to lesser smoke, HC and CO, whereas NO_x emissions were reduced by retarding the injection timing because of lower combustion temperature in the cylinder. Pandian et al. [49] investigated the influence of injection timing on performance and emission of *Pongamia* biodiesel-diesel blends. When injection timing was advanced from 18° to 30° bTDC, CO, HC, and smoke emissions were reduced with an increase in NO_x emissions, and the best performance parameters were obtained at 21° bTDC. Advanced injection timing gave increased in-cylinder peak pressure and the increase in the oxides of nitrogen was within acceptable limits for methyl tallow ester and methyl soy oil ester [99]. The engine also showed low carbon monoxide and unburned hydrocarbon emissions and there was no perceptible changes in BSFC and smoke levels at advanced engine timing. The impact of injection timing on the performance of mahua methyl ester was studied by Raheman and Ghadge [100]. The results showed that there was significant decrease in BSFC and EGT and an increase in BTE to meet the performance in par with the diesel fuel when injection timing was advanced. Monyem et al. [101] studied the influence of injection timing on biodiesel and found that there was significant decrease in CO and HC emissions in a range of injection timing and NO_x emissions were increased by 3° advance and reduced considerably by 3° retardation from the default injection timing. Gumus et al. [102] reported that original timing gave the best results for BSFC, BSEC and BTE compared to advanced and retarded injection timing for canola oil methyl ester. Though they have not reported any effect of injection timing on emissions, but shows that varying injection timing may not help obtaining best results, but optimum results may be achieved with this strategy to get a balance between performance and emissions. Retarded injection timing was also beneficial in reducing NO_x, CO, and HC emissions, while increasing BTE, CO_2 and smoke under all loading conditions when fuelled with waste plastic oil [103]. Hariram and Kumar [104] investigated the effect of injection timing on combustion, performance and emission parameters of diesel engine fuelled with algal oil methyl ester (AOME). They found that by advancing injection timing, could improve BSFC and reduce HC, CO and smoke with increase in heat release rate, BMEP and NO_x, while retardation resulted in marginal improvement in heat release rate, BMEP and NO_x emissions with increase in BSFC, HC, CO and smoke. Finally they found optimum injection timing to be 340 CAD which demonstrated better combustion and performance with minimal emissions.

Varying fuel injection timing also benefits the dual fuel engines in terms of improving thermal efficiency and reducing emissions. Abd Alla et al. [105] studied the effect of injection timing on dual fuel in order to reduce the emissions and improve the thermal efficiency at lower loads. Interestingly, when the injection timing of the pilot fuel was advanced thermal efficiency was improved with some compensational increase in the NO_x emissions and reduction in CO and HC. However at medium and high loads advancing injection timing led to early knocking. Therefore the advanced timing of pilot fuel in dual fuelled engines was not beneficial for medium and high loads. Noguchi et al. [106] also reported that retardation of injection timing of pilot fuel in diesel–alcohol dual fuel helped in reducing the knocking in engines. Sayin et al. [107,108] investigated the impact of injection timing on diesel alcohol dual fuel. It was observed that retarding injection timing from original timing resulted in increased CO and HC and reduced NO_x and CO2 emissions, while results were reversed when the injection timing was advanced from original default value. Kegl [109] found the optimal injection timing for biodiesel fuelled engine for reduced harmful emissions and better performance. The optimized injection timing was found to be 19° bTDC, having a 25% reduction in CO and NO_x and a 30% reduction for HC and a 50% reduction in smoke, also with a 5% reduction in engine power output and a 10% increase in BSFC. Injection timing was also proved to be an effective method to find optimum balance between performance and emissions for engine powered by natural gas [110,111]. Mohammed et al. [112] conducted experiments to investigate the effects of injection timing on engine

characteristics and emissions of a DI engine fuelled with NG—hydrogen blends (0; 3; 5; 8%). Three injection timing (120°; 180°; 300° bTDC) were chosen for their study. It was found that the performance and NO_x emission were higher for 180° bTDC followed by 300° bTDC and 120° bTDC. The total HC and CO were found to decrease while CO_2 was found to increase with advancing injection timing.

4.2. Effect of injection timing on low heat rejection (LHR) engine

The engines with thermal barrier coating to reduce heat transfer between in-cylinder gas and coolant is low heat rejection engines (LHR). Some important advantages of LHR engines are improved fuel economy, reduced engine noise, higher energy in exhaust gases and multi-fuel capability of operating low cetane fuels, but the main disadvantage is high level of NO_x emissions. Injection timing also proved to reduce NO_x emissions from low heat rejection engines [113]. Kamo et al. [114] suggested retarding injection timing results in fuel economy improvement apparently at all speeds due to higher premix combustion, lower diffused combustion and reduced heat transfer losses. Parlak et al. [115] studied the effect of injection timing on low heat rejection indirect injection engines in the aim of reducing NO_x. When NO_x-BSFC trade off was considered, retarding the fuel injection timing by 4° CA resulted in a maximum of 40% reduction in NO_x. Buyukkaya and Cerit [116,117] also studied the effect of injection timing on LHR engine. By retarding 2° from the original timing of 18° bTDC, there was a reduction of 2 and 11% in BSFC and NO_x, respectively.

In general, advancing the injection timing will benefit in better performance with increase in NO_x and smoke whereas retarded fuel injection timing results in better NO_x and smoke emissions with no or little deterioration to the engine performance in terms of fuel consumption and thermal efficiency.

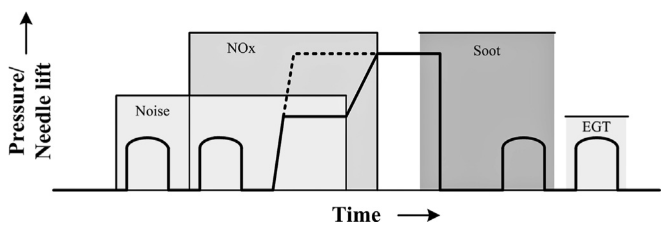

Fig. 8. Typical multiple injections used in engines.

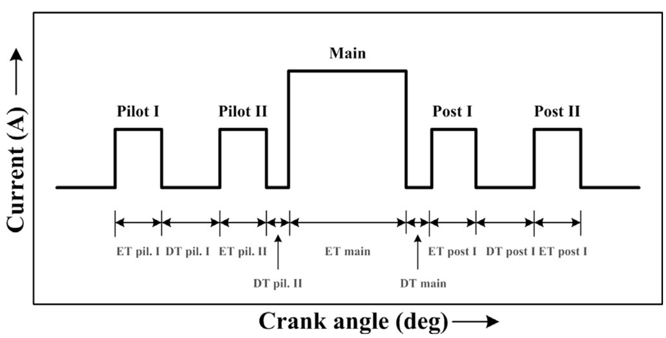

Fig. 9. Injection profile nomenclature.

5. Split/multiple injections

Nowadays, high pressure common rail fuel injection systems allow a very high degree of flexibility in the timing and quantity control of multiple injections, which can be used to obtain significant reductions in engine noise and emissions without compromising its performance and fuel consumption. Fig. 8 shows typical multiple injections and its benefits on engine performance and emission reductions. One or two pilot injections at low pressure help in reducing engine noise as well as NO_x emissions. Either rectangular shape i.e. fully opened needle or boot type rate shaped main injection will aid in NO_x reduction in support to close pilot injections. Coupled post injection with high pressure will help in reducing soot emissions while late post injection at moderate pressure helps to manage exhaust gas temperature for regeneration of diesel particulate filter and to provide hydrocarbons for NO_x adsorber catalyst [118].

The nomenclature of injection profile can be interpreted from Fig. 9 which consists of two pilot injections and two after/post injections. The main parameters of the injection profile are start of injection (SOI), energizing time of an injection or injection duration (ET) and dwell time, which is the time interval between the end of an injection and the start of the following one (DT) [119].

Multiple injection or split injections have been proposed as a means to decrease particulate emissions significantly without a

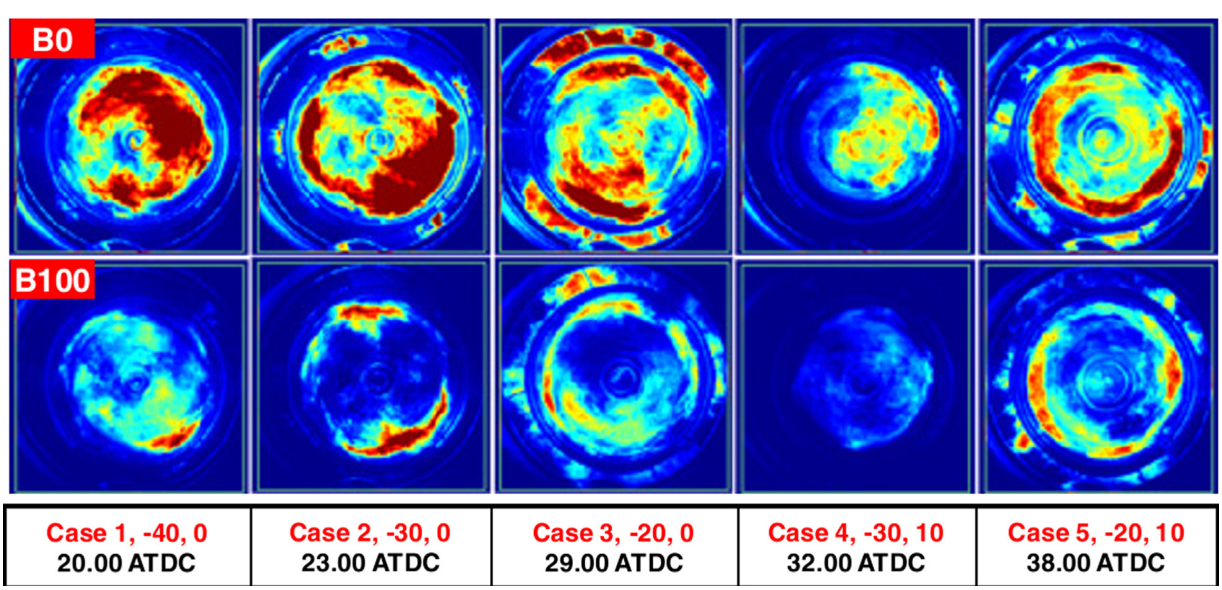

Fig. 10. Combustion images of biodiesel and diesel with pilot injections [130].

substantial compensation in NO_x emissions [120,121]. However Considerable retardation of injection timing was possible by using pilot injection, and combination of pilot injection and higher injection pressure controlled simultaneous reduction in NO_x by 35% and smoke by 60–80% without worsening the fuel economy compared with single injection [122]. In spite of injection timing, dwelling time between two consecutive injections also plays a major role in performance and emissions. When dwelling time was reduced, the fuel of the second injection was burned closer to TDC, resulting in lower fuel consumption, however combustion noise increased with shorter dwelling time and smoke emission got increased, which was related to the characteristics of low temperature combustion, where an increase in local burning temperature led to higher soot formation [123]. Durnholz et al. [124] studied the effect of pilot injection on combustion noise, performance and emissions and they found that by using a pilot injection, noise level was decreased by 10 dBA when it was used at optimum condition and NO_x emissions was reduced by 30% and HC could be cut down to half while black smoke levels could be kept constant. Later Pierpont et al. [125] used multiple injection strategy to reduce both NO_x and particulate emissions. Interestingly they found optimized multiple injection by varying fuel distribution in each pulse and the dwelling time between pulses for each operating condition with reduced particulates, however it came with a penalty of increased BSFC by 3–4%. Tow et al. [126] reported that by implementing triple injections gave better results compared to single and double injections, however double injection with long delay between successive injections reduced particulates by a factor of three with no increase in NO_x. An increasing separation between pilot and main injection also reduced NO_x but long delay might lead to high smoke, similarly closer post injection might lead to reduced particulate emissions while increasing delay beyond certain point might result in steep increase in BSFC and HC emission [127]. Dividing the pilot injection into a number of smaller injections helps to further decrease the noise while suppressing the increase of fuel consumption and HC emissions. These effects results from the enhanced heat release rate of pilot injection fuel, which is due to the reduction of fuel impingement on the cylinder wall. However at light loads, fuel quantity of pilot injection should be decreased and the injection must be prior to the main injection for suppressing the possible increase in smoke and HC. Post/after injection should be immediately injected after main injection in order to reduce smoke, HC and fuel consumption. Combustion of early pilot injection generates mild heat release in two stages consisting of cool flame and hot flame combustion. The premixed combustion due to early pilot injection causes mild increase in cylinder pressure and shortens the main ignition delay leading to decrease

Table 1
Summary of injection strategies on engine performance and emissions.

Author	Strategy used	Fuel	BSFC	NO_x	HC	CO	Smoke
Icıngur and Altiparmak [35]	Injection pressure	Diesel	↓	↑	na	na	↓
Celıkten et al. [36]	Injection pressure	Diesel	↓	↓	na	na	↓
Gumus et al. [42]	Injection pressure	Biodiesel blends	↓	↑	↓	↓	↓
Sayin and Gumus [43]	Injection pressure	Biodiesel blends	↓	↑	↓	↓	↓
Canakci et al. [44]	Injection pressure	Methanol blends	↑↓	↑	↓	↓	↓
Purushothaman et al. [45,46]	Injection pressure	Orange skin powder solution in diesel	↓	↑	↓	↓	↓
Puhan et al. [47]	Injection pressure	Linolenic methyl ester	↓	↑	↓	↓	↓
Jindal et al. [48]	Injection pressure	*Jatropha* methyl ester	↓	↓	↓	↑	↓
Pandian et al. [49]	Injection pressure	*Pongamia* methyl ester	↓	↑	↓	↓	↓
Sayin and Gumus [43]	Injection pressure	Biodiesel blends	↓	↑	↓	↓	↓
Belagur and Chitimini [50]	Injection pressure	Hone oil and blends	↓	↑	↓	↓	↓
Kannan and Anand [51]	Injection pressure	Waste plastic oil	↓	↓	na	na	↓
Pierpont and Reitz [53]	High injection pressure	Diesel	↑↓	↑	na	na	↓
Su et al. [54]	High injection pressure	Diesel	na	↑	na	na	↓
Dodge et al. [55]	High injection pressure	Diesel	↑	↑	na	na	↓
Pickett and Siebers [56]	High injection pressure	Diesel	na	na	na	na	↓
Nishimura et al. [67]	Injection rate shaping	Diesel	↑	↓	na	na	↓
Beck and Chen [84]	Injection rate shaping	Diesel	↑	↓	na	na	↑
Benajes et al. [83]	Injection rate shaping	Diesel	↑	↓	na	na	↑
Desantes et al. [86,87]	Injection rate shaping	Diesel	↑	↓	na	na	↑
Suryawanshi and Deshpande [95]	Injection timing	*Pongamia* methyl ester	↑↓	↓	↓	↓	na
Nwafor et al. [96]	Injection timing	Rapeseed oil	↑	na	na	na	na
Reddy and Ramesh [97]	Injection timing	*Jatropha* oil	↓	na	↓	na	↓
Ganapathy et al. [98]	Injection timing	*Jatropha* methy ester	↓	↑	↓	↓	↓
Sayin and Gumus [43]	Injection timing	Biodiesel blends	↑↓	↑	↓	↓	↓
Pandian et al. [49]	Injection timing	*Pongamia* methyl ester	↓	↑	↓	↓	↓
Yahya and Marley [99]	Injection timing	Methyl tallow ester and methyl soy oil ester	↑↓	↑	↓	↓	↑↓
Raheman and Ghadge [100]	Injection timing	Mahua methyl ester	↓	na	na	na	na
Monyem et al. [101]	Injection timing	Biodiesel	na	↑	↓	↓	na
Gumus et al. [102]	Injection timing	Canola methyl ester	↓	na	na	na	na
Mani and Nagarajan [103]	Injection timing	Waste plastic oil	↓	↓	↓	↓	na
Hariram and Kumar [104]	Injection timing	Algal oil methyl ester	↓	↑	↓	↓	↓
Abd Alla et al. [105]	Injection timing	Dual fuel	↓	↑	↓	↓	na
Sayin et al. [107,108]	Injection timing	Diesel alcohol dual fuel	na	↓	↑	↑	na
Kegl [109]	Injection timing	Biodiesel	↑	↓	↓	↓	↓
Mohammed et al. [112]	Injection timing	Natural gas and hydrogen	na	↑	↓	↓	na
Shundoh et al. [122]	Multiple/split injection	Diesel	↑↓	↓	na	na	↓
Durnholz et al. [124]	Multiple/split injection	Diesel	na	↓	na	na	↓
Pierpont et al. [125]	Multiple/split injection	Diesel	↑	↓	na	na	↓
Chen [127]	Multiple/split injection	Diesel	↑	↓	↑	na	↓
Choi and Reitz [129]	Multiple/split injection	Oxygenated fuel blends	na	na	na	na	↓
Fang and Lee [130]	Multiple/split injection	Biodiesel	na	↓	na	na	na

↑—Increase,↓—decrease, ↑↓—no significant effect, na—data not available.

in combustion noise and also reduces smoke by enhanced mixing of air in the cylinder [128].

Choi and Reitz [129] studied the effect of split injection on oxygenated fuel blends at low and high low load conditions. At high loads, split injections compared to single injection had a favourable effect on soot emissions, similarly at low loads, split injection helped in reducing particulate emissions compared to single injections. Later, Fang and Lee [130] showed that split injection are beneficial in reducing NO_x in biodiesel fuel. They also visualized the combustion phenomena of split injection inside the combustion chamber (Fig. 10). From the combustion chamber luminosity images, it is clear that NO_x formation in biodiesel is lesser than diesel by changing pilot injection timing and retarding the main injection.

Split injections helps in reducing diesel engine exhaust emissions and when optimized it will produce better NO_x-PM trade off with comparatively better performance when compared with single injection and using other injection strategies.

6. Conclusion

A review was conducted over the literature concerning emission control in diesel engine by different fuel injection strategies. The strategies covered in this review are varying injection pressure, injection timing, injection rate shape and split/multiple injections. Researchers have carried out many experimental works to study the effect of injection strategies on engine performance and emission formation. Table 1 shows the summary of the extensive review done on the injection strategies. The table gives an insight on the effect of various strategies on performance and emissions achieved experimentally. Some of the prominent points showing the effect of above listed strategies on engine performance and emissions for diesel and other biofuels are listed below

- Increasing injection pressure, in general, results in increased thermal efficiency and better fuel consumption and less CO, HC and smoke emissions, however with higher NO_x.
- Ultra high injection pressures results in reduction of soot emissions mainly attributed by better spray atomisation and air entrainment, however leads to increased NO_x and BSFC. Very high injection pressures also have significant effect on soot particle size distribution.
- Injection rate shaping is a better strategy in reducing NO_x at certain loading conditions, but using ramp or boot shaped injection rates always is accompanied by increased soot formation and fuel consumption. Injection rate shaping has been proved to decrease combustion noise.
- Advanced injection timing results in increased NO_x while reduced fuel consumption, and emissions like CO, HC and smoke, although advancing beyond certain limit may result in high smoke and poor performance. Combined with high injection pressures may lead to reduced particle number concentration.
- Similarly retarding injection timing results in reduced NO_x, while increasing other emissions such as CO, HC and smoke and also deteriorates fuel consumption.
- In general, an optimized timing has to be found for any engine and fuel to strike a balance between performance and emissions.
- Pilot injection help in reducing combustion noise and NO_x emissions and immediate post injection may help in soot oxidation and late post injection helps in regeneration of diesel particulate filter.
- Multiple injections are known for reducing both NO_x and PM emissions simultaneously, but immense trials have to be carried out in prior to fix various parameters like dwell time, injection time and duration of all injections to balance emissions and performance of the engine.

Many studies have shown comprehensively that there is a very large, still unexploited potential for improvements in fuel injection parameters. In overall, based on engine operating and design parameters, the type of fuel injection strategy or combination has to be chosen accordingly. Generally combination of one or more strategies may help to strike a balance between reducing emissions and improve the performance of the engine. These also provide major reductions in pollutions particularly with respect to NO_x and PM reduction and hence provide the flexibility in controlling the PM-NO_x trade-off for future vehicles to meet more and more stringent emission norms.

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